III.E Controls & Diagnostics

III.E.1 An Investigation to Resolve the Interaction between Fuel Cell, Power Conditioning System and Application Load

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Objectives

- Develop nonlinear transient component and system models for tubular solid oxide fuel cell (TSOFC) power-conditioning system (PCS).
- Analyze the effect of load transients and switching, and low-frequency ripples on the performance and reliability of the TSOFC.
- Conduct parametric studies of balance-of-plant subsystem (BOPS) for TSOFC PCS optimization.
- Investigate the load-transient-mitigation effectiveness of two energy-buffering schemes (battery and pressurized hydrogen tank) on the performance and durability of the solid oxide fuel cell (SOFC).

Approach

- Initially a multi-software TSOFC PCS model was developed using the following scheme:
  - TSOFC temporal model [1, 2] was developed on a Visual Fortran platform.
  - BOPS model was developed using gPROMS, a powerful nonlinear solver.

  - Power electronics subsystem (PES) and application load (AL) models were developed using SaberDesigner, a sophisticated and powerful circuit and system simulator.
  - The overall TSOFC PCS model was realized by integrating the four component models (i.e., TSOFC, PES and AL, and BOPS) using iSIGHT, which is a powerful software management tool.
  - TSOFC spatial model is implemented using TOPAZ [4], which is a powerful finite-element-analysis software originally provided by Lawrence Berkeley National Laboratory.
- Subsequently, on suggestion from Solid State Energy Conversion Alliance (SECA) industry members and the National Energy Technology Laboratory (NETL), the TSOFC component and system models have been implemented in a "low-cost" Matlab/Simulink environment for easy use by the SECA industry members. It is also anticipated that Matlab/Simulink will provide a better avenue for real-time simulation, which may be required for long-term analysis studies.
- Objective 1 has been accomplished; however, effort is being made to enhance the computational speed for long-term reliability studies. Detailed work on objectives 2 through 4 has been done.

Accomplishments

- Developed the TSOFC temporal model based on fundamental electrochemical equations [1, 2]. The transient modeling technique is based on the Lagrangian approach, which involves focusing attention on each fluid element of the SOFC and calculating the mass and energy balances for each individual element during the transient.
- Developed the temporal BOPS model consisting of the fuel-processing subsystem for conversion of natural gas to hydrogen and thermal-management and power recovery subsystems to maintain fuel and oxidant temperatures for efficient chemical reactions.
- Developed optimal PES topology for SOFC PCS, consisting of a DC-DC boost converter to step up the SOFC output voltage followed by a DC-AC inverter and residential load profile.
- Integrated all the models in MATLAB/Simulink platform to obtain a comprehensive transient TSOFC PCS model.
- Analyzed the effect of the load transient on the material of the TSOFC.

Future Directions

- Development of fully transient spatial model for planar SOFC (PSOFC) configurations.
- Development of enhanced BOPS model and investigation of additional BOPS component models consistent with possible configuration changes which accommodate fuel reforming and application loads.
- Optimal PES design and design methodology using updated PES transient models (including a variety of additional nonlinear topologies for stationary and mobile applications) for enhanced PSOFC performance.
- Detailed parametric studies to determine best-practice control strategies and component design and possible configuration changes based on NETL guidelines.
- Validation of the models and verification of simulation results.

Introduction

Differences in the response times of a solid oxide fuel cell (SOFC), its power-electronics subsystem (PES), and the balance-of-plant subsystem (BOPS) cause low-reactant conditions near the SOFC during load transients. Because the BOPS cannot instantaneously provide enough fuel to the SOFC, load transients have a detrimental effect on the performance and durability of the fuel cell. To alleviate the degrading effects of load transients on the performance and durability of SOFC stacks, we investigate the effects of energy-storage devices, namely pressurized hydrogen storage tanks and batteries, and optimize their costs and size. Finally, using finite-element analysis, we

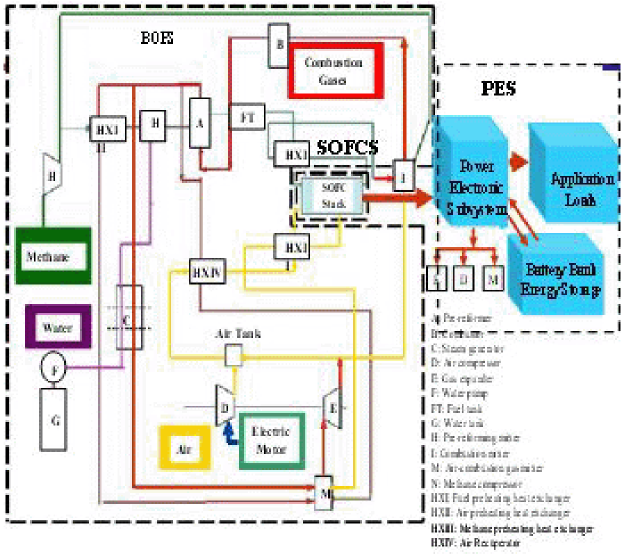

Figure 1. Block Diagram of a Complete SOFC PCS Comprising the SOFC Stack, PES, and the BOPS Supplying Power to the Application Load

compare the effectiveness of two inverter-modulation strategies (space-vector modulation and sinusoidal pulse-width modulation) during load transients by resolving their impacts on SOFC hydrogen utilization and current density.

Approach

The overall interaction analysis, to ascertain the efficacy of energy-buffering devices and control techniques on improving the performance of the SOFC stack during a load transient, is carried out in two steps. First, a time-domain analysis of the SOFC PCS is carried out using the comprehensive model as shown in Figure 1. Using such a temporal analysis, we obtain the change in SOFC stack output current and voltages before, during, and after a load transient. Next, to translate system-level electrical parameters of the SOFC stack to its cell-level electrochemical parameters (such as current-density and cell-temperature distributions), a detailed finite-element analysis (FEA) is conducted using the spatial model of the SOFC stack [4]. Because SOFC parameters like hydrogen depletion and cell temperature can directly affect the material properties of the SOFC and hence impact its performance and durability, it is important to study the spatial distribution of these parameters across its cross-section.

Using the FEA [4], thermal conduction effects are coupled with electrical conduction effects, and local electrical and chemical properties are rigorously computed across the SOFC cross-section. Temperature dependencies of material properties are also incorporated into the SOFC model. The effective resistance of each component (interconnect, anode, cathode, and electrolyte) is computed by FEA from actual cell geometry and temperature-dependent conductivity. Current density is calculated at each electrolyte element from the local electrode potential, overpotential function and local bulk gas chemical potential. Hydrogen utilization is directly proportional to the current drawn by the PES and can be defined as $U = I/n(\dot{n} F)$ where $\dot{n}$ is the hydrogen flow rate which is determined by the BOPS and nF determines the charge flow between the anode and the cathode. Finally, SOFC temperature is obtained by using basic thermodynamic equations [2]. These results are used to relate the SOFC current to the cell temperature. Theoretical studies indicating interaction between the standard cathode, $(La_{0.85}Sr_{0.15})_{0.95}MnO_3$ (LSM), and the standard electrolyte (yttria-stabilized zirconia) above temperatures of 1000°C [6] say that in long-term operation, an interlayer of $LaZr_2O_7$ forms whose conductivity is much less than that of LSM and, hence, has an impact on the output voltage and current supplied by the SOFC.

Results

The load transient causes a significant increase in the load current and hence the current density inside the cell. This causes a drop in the cell voltage (Figure 2(a)) because of higher polarization. Because the response time of the BOPS is significantly lower than the response time of the PES/SOFC, the input fuel flow rates of the SOFC stack do not change soon after the load transient. This leads to higher fuel utilization inside the SOFC stack for it to attain a new electrochemical steady state. Figure 3 shows that hydrogen (fuel) utilization and current density increase very sharply immediately after the load transient. As expected, hydrogen utilization is higher at the SOFC stack outlet than at the SOFC stack inlet.

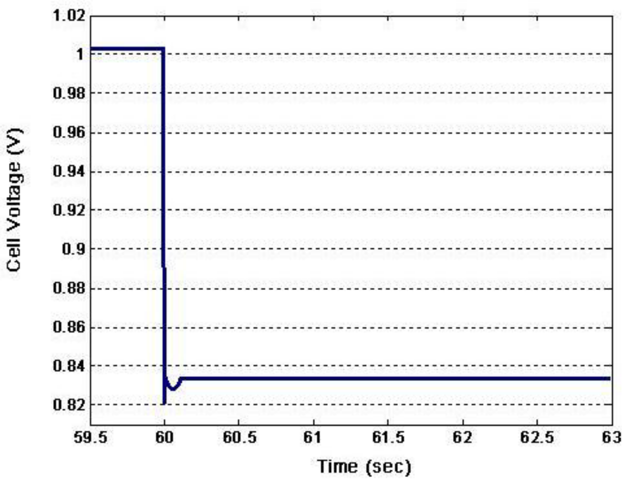

Figure 2(a). Response of the Fuel Cell Voltage Due to the Sudden Load Transient

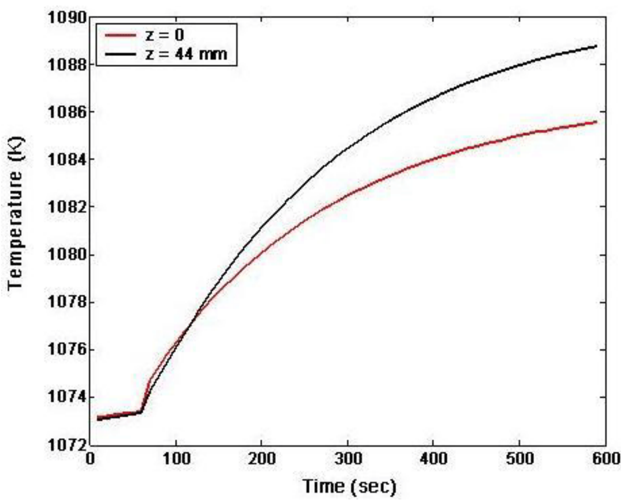

Figure 2(b). Variation of Temperature Due to Load Transients

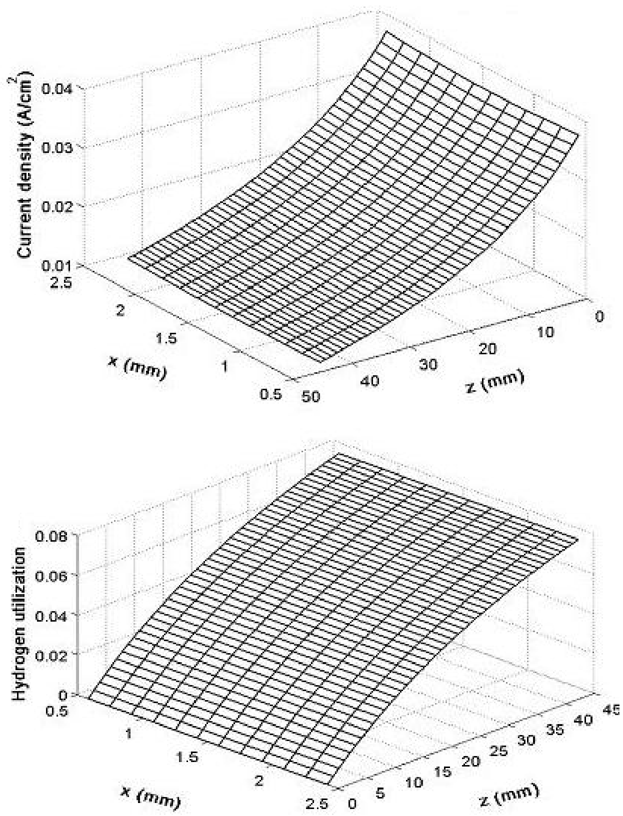

Figure 3. Spatial Variation of Current Density and Spatial Distribution of Hydrogen Utilization Inside the Fuel before the Load Transients

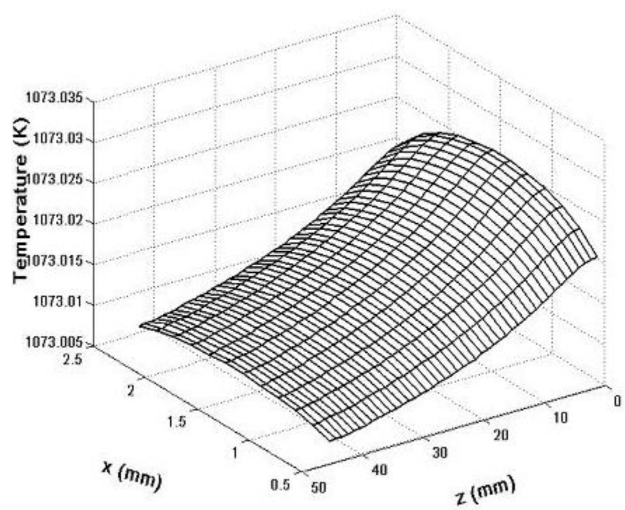

Figure 4. Spatial Variation of Temperature Inside the Solid Oxide Fuel Cell before Load Transients

The fuel-cell temperature increases with time for increased fuel utilization. However, the thermal time constant of the SOFC stack being much larger than that of the SOFC electrochemical or PES time constant [5], the cell temperature increases gradually, as validated in Figure 2(b), until the SOFC attains a new thermal equilibrium. Figure 4 shows the spatial variation of temperature across a cross-section of the SOFC. This indicates that, to protect the SOFC from the degrading effects of the load transients, the BOPS should be fast enough to prevent such an increase in the temperature. However, in reality, response time of the BOPS is not fast and, as such, load-transient mitigation techniques are needed.

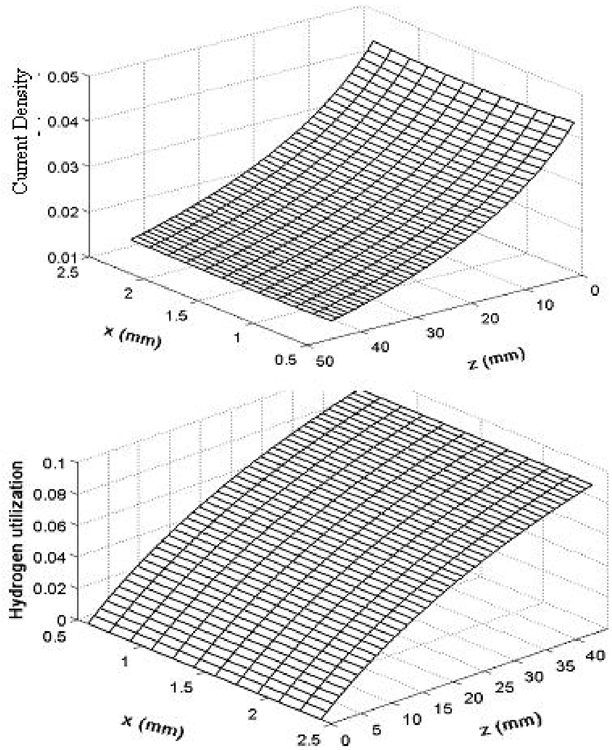

Figure 5. Spatial Variation of Current Density and Spatial Distribution of Hydrogen Utilization Inside the Fuel Cell during the Load Transients with Battery

During the load transient, the energy-buffering devices supply the additional energy requirements to the load; hence, the load demands of the SOFC are substantially reduced. Figure 5 shows the current density of the SOFC after the load transient. Clearly, the energy buffering ensures practically no change in the current density of the SOFC after the transient. Consequently, the increase in fuel utilization as well as the accompanying temperature rise is negligible.

The transient response of the SOFC using sine-wave pulse width modulation (SPWM) and bus-clamped space-vector modulation (SVM) has been analyzed. We observe an improved SOFC stack output current response as in Figure 6 but minimal effect on the hydrogen utilization when bus-clamped SVM is used as the modulation technique; this is attributed to the improved utilization of the DC bus by the inverter using bus-clamped SVM.

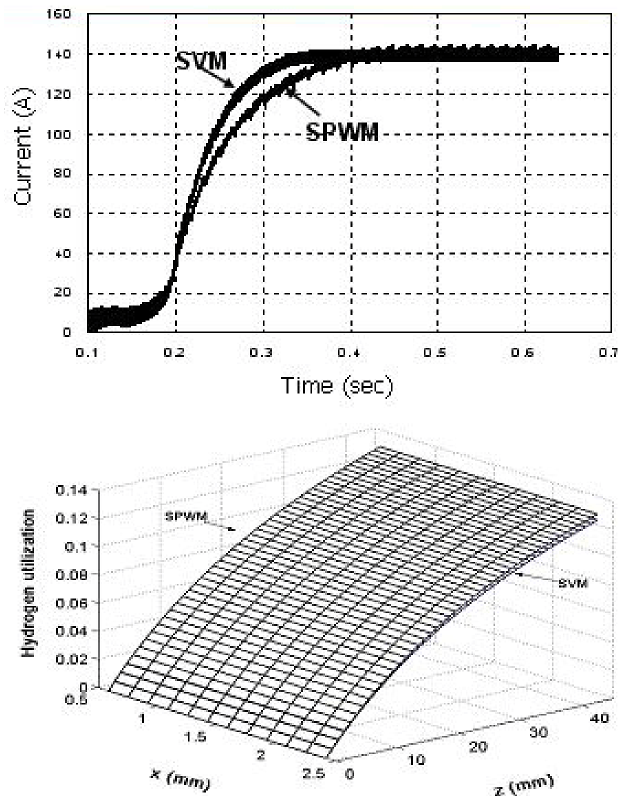

Figure 6. (a) SOFC Input Current during Load Transient Showing Difference between SPWM and Bus-Clamped SVM (b) Spatial Distribution of Hydrogen Utilization during the Load Transient

Conclusions

We investigate the effects of load transients on the performance and durability of SOFCs and how energy-buffering devices can be used to mitigate the detrimental effects of these load transients. The use of pressurized hydrogen tanks (PHTs) and batteries for load-transient mitigation are considered.
Using optimization techniques with cost and size as the constraints, optimal battery and PHT sizes are obtained for a particular response time while ensuring that the SOFC reliability is not compromised.

The impacts of advanced PES modulation and control strategies on SOFC reliability are investigated. We observe that bus-clamped SVM, as compared to SPWM, of the inverter yields faster dynamic response under load transients. While the superior dynamic performance capability of (bus-clamped) SVM for three-phase inverters is well known, what is often overlooked in such analysis is the need for a stiff DC voltage source. As such, for SOFC, which is not a stiff DC voltage source, the enhanced performance of SVM comes at the cost of higher localized current densities and fuel flow rates, which may be detrimental to the SOFC stack. Non-uniformities during load transients will result in localized oxidization of SOFC electrolyte material, which could result in reduced conductivity because of the formation of $LaZr_2O_7$.

However, the detrimental effects of SVM can be overcome if it is used in conjunction with energy storage devices because such energy storage devices can almost instantaneously supply the excess energy required during load transients; hence, such techniques can be used to maintain a stiff DC input voltage to the converters. Such a SOFC power-conditioning system (PCS) would ensure better load-following and hence lead to improved SOFC PCS performance.

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FY 2004 Publications/Presentations

1. S.K. Mazumder, K. Acharya, C. Haynes, R. Williams, M.R. von Spakovsky, D. Nelson, D. Rancruel, J. Hartvigsen, and R. Gemmen, "Solid-oxide-fuel-cell performance and durability: resolution of the effects of power-conditioning systems and application loads", *Special Issue, IEEE Transactions on Power Electronics*, 2004.

2. S.K. Mazumder, K. Acharya, S.K. Pradhan, J. Hartvigsen, C. Haynes, and M.R. von Spakovsky, "Energy-buffering and control techniques for load transient mitigation of solid-oxide fuel cell (SOFC) power conditioning system (PCS)", accepted for publication, *IEEE Power Electronics Specialists Conference*, 2004.

3. K. Acharya, S.K. Mazumder, R.K. Burra, C. Haynes, and R. Williams, "Solid-oxide fuel cell (SOFC) power-conditioning systems interaction analyses: Resolution of the electrical-feedback effects on performance and durability", *IEEE Applied Power Electronics Conference*, February 2004.

4. M.R. von Spakovsky, D. Nelson, D. Rancruel, S.K. Mazumder, K. Acharya, C. Haynes, and R. Williams, "Investigation of system and component performance and interaction issues for solid-oxide fuel cell based auxiliary power units responding to changes in application load", *IEEE Industrial Electronics Conference*, 2003.

Special Recognitions & Awards/Patents Issued

1. Publication of interaction analysis work in a **Special Issue** of Distributed Generation of "prestigious" IEEE Transactions on Power Electronics.

2. **Invited Paper** (*please see paper #4 under 'FY 2004 Publications/Presentations'*) in a Special Session on Fuel Cell Power Systems at the "prestigious" IEEE Industrial Electronics Conference, Roanoke, Virginia.